Seasonal Dynamics of Active Soil Carbon and Nitrogen Pools under Intensive Cropping in Conventional and No Tillage

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Summary - Zusammenfassung

Active fractions of soil carbon (C) and nitrogen (N) can undergo seasonal changes due to environmental and cultural factors, thereby influencing plant N availability and soil organic matter (SOM) conservation. Our objective was to determine the effect of tillage (conventional and none) on the seasonal dynamics of potential C and N mineralization, soil microbial biomass C (SMBC), specific respiratory activity of SMBC (SRAC), and inorganic soil N in a sorghum [*Sorghum bicolor* (L.) Moench]-wheat (*Triticum aestivum* L.)/soybean [*Glycine max* (L.) Merr.] rotation and in a wheat/soybean double crop. A Weswood silty clay loam (fine, mixed, thermic Fluventic Ustochrept) in southcentral Texas was sampled to 200 mm depth 57 times during a 2-yr period. Potential C mineralization was lowest ($\approx$2 to 3 g · m^{-2} · d^{-1}) midway during the sorghum and soybean growing seasons and highest ($\approx$3 to 4 g · m^{-2} · d^{-1}) at the end of the wheat growing season and following harvest of all crops. Addition of crop residues increased SMBC for one to three months. Potential N mineralization was coupled with potential C mineralization, SRAC, and changes in SMBC at most times, except during the wheat growing season and shortly after sorghum and soybean residue addition when increased N immobilization was probably caused by rhizodeposition and residues with low N concentration. Seasonal variation of inorganic soil N was 19 to 27%, of potential C and N mineralization and SRAC was 8 to 23%, and of SMBC was 7 to 10%. Soil under conventional tillage experienced greater seasonal variation in potential C and N mineralization, SRAC, bulk density, and water-filled pore space than under no tillage. High residue input with intensive cropping and surface placement of residues were necessary to increase the long-term level of active C and N properties of this thermic-region soil due to rapid turnover of C input.

Jahreszeitliche Veränderungen des aktiven Kohlenstoffs und Stickstoffs im Boden bei intensivem Pflanzenbau mit konventioneller Bodenbearbeitung und bearbeitungsfreiem Ackerbau

Umweltfaktoren und Bewirtschaftungsmaßnahmen können den Pool des aktiven Kohlenstoffs und Stickstoffs im Boden verändern und so die N-Verfügbarkeit sowie den Humusgehalt beeinflussen. Unsere Zielstellung war, den Effekt der Bodenbearbeitung (konventionelle und Direktsaat) auf die jahreszeitlichen Schwankungen von potentieller C- und N-Mineralisierung, dem bodenmikrobiellen Biomasse-C (SMBC), der spezifischen Atmungsaktivität der SMBC (SRAC) und dem mineralischen N in einer Sorghum [*Sorghum bicolor* (L.) Moench]- Weizen (*Triticum aestivum* L.)/Sojabohnen [*Glycine max* (L.) Merr.] Fruchtfolge und in einem Weizen/Sojabohnen Doppelanbau zu bestimmen. Hierzu wurden auf einem Feldversuch in Süd-zentral-Texas (Weswood, schluffig toniger Lehm) innerhalb von zwei Jahren 57 Bodenproben (0 bis 200 mm) genommen. Die potentielle C-Mineralisierung war während der Sorghum- und Sojabohnen-Wachstumsperioden am niedrigsten ($\approx$2 bis 3 g m^{-2} d^{-1}) und am Ende der Weizenwachstumsperiode und nach der Ernte aller Kulturen am höchsten ($\approx$3 bis 4 g m^{-2} d^{-1}). Die Ernterückstände erhöhten SMBC für ein bis drei Monate. Die potentielle N-Mineralisierung war mit der potentiellen C-Mineralisierung, mit SRAC und mit SMBC positiv korreliert, außer während der Wachstumsperiode von Weizen und kurz nach der Ernte von Sorghum und Sojabohnen, wenn vermutlich Rhizodeposition und Pflanzenrückstände mit niedriger N-Konzentration N-Immobilisierung verursachten. Die jahreszeitlichen Schwankungen von mineralischem N betrugen 19 bis 27%, von potentieller C- und N-Mineralisierung und SRAC 8 bis 23% und von SMBC 7 bis 10%. Mit konventioneller Bodenbearbeitung waren die jahrezeitlichen Schwankungen von potentieller C- und N-Mineralisierung, SRAC, der Bodendichte und des wasserführenden Porenvolumens größer als mit Direktsaat. Hohe Produktion an Pflanzenrückständen bei intensivem Anbau und ihre Rückführung auf die Bodenoberfläche waren aufgrund des schnellen Abbaus des C-Inputs zu diesem Boden in der warm-temperierten Region nötig, um den langjährigen Gehalt an aktivem C und N zu erhöhen.

1 Introduction

Inorganic and labile soil N pools are essential for plant nutrition, but can threaten water quality when excessive. To meet goals of profitability and environmental protection, a delicate balance in the inorganic soil N supply must be managed with knowledge of seasonal changes in soil N mineralization/immobilization.

The ability to predict *in situ* soil N mineralization from N mineralized under optimum conditions with adjustment

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for seasonal changes in temperature and moisture has been significantly advanced with the development of the leaching-incubation method (*Stanford* et al., 1973; *Stanford & Epstein*, 1974). However, using this approach the quantity of N mineralized during the growing season has been underpredicted (*Campbell* et al., 1981) and overpredicted (*Cabrera & Kissel*, 1988). A reason for discrepancies between potentially mineralizable N determined from a sample collected before the growing season and actual net N mineralized during the growing season may be changes in C input via rhizodeposition (*i.e.*, root exudates, mucilage, sloughed cells, etc.) that affect N mineralization/immobilization (*Mary* et al., 1993).

Abundant, easily-decomposable organic substrates with low N concentration such as crop root-derived material or crop residues often lead to temporary net N immobilization (*Mary* et al., 1993), since N transformations are linked to C dynamics (*Jansson & Persson*, 1982). Nitrogen that was immobilized into a growing pool of soil microbial biomass (SMB) becomes mineralized as the SMB decreases with declining substrate availability. Measurement of seasonal changes in SMB and potential C and N mineralization are therefore, important in understanding the dynamics of inorganic soil N supply.

Crop residue input, especially with low N concentration, can cause significant N immobilization as a result of high microbial activity (*Marstorp & Kirchmann*, 1991; *Vigil & Kissel*, 1991). However, little information is available from field studies on the effects of crop growth on seasonal changes in active soil C and N pools. Significant C input via rhizodeposition has been shown during growth of wheat (*Swinnen* et al., 1994), indicating the need to better characterize seasonal changes in potential N mineralization. We found large seasonal changes in active soil C and N pools in monoculture cropping systems having six to seven months of fallow (*Franzluebbers* et al., 1995c). However, in the southern USA, double-cropping systems can be a viable alternative to traditional monoculture systems to increase profitability, as well as increase crop diversity and maintain SOM for a more sustainable agriculture. In addition, no tillage (NT) management is growing in popularity for greater soil and water conservation, yet little information is available on the impact of tillage regime on seasonal changes in acitve soil C and N.

Our objectives were to (i) determine the seasonal pattern of potential C and N mineralization, SMBC, specific respiratory activity of SMBC, and inorganic soil N and (ii) relate these seasonal changes to differences in crop growth stage and residue inputs as affected by tillage and crop sequence.

2 Materials and Methods

2.1 Crop Management and Site Characteristics

A long-term field experiment was initiated in 1982 in the Brazos River floodplain in southcentral Texas (30° 32′ N, 94° 26′ W). Intensive cropping sequences of continuous wheat/soybean double crop and sorghum rotated with a wheat/soybean double crop were managed under conventional tillage (CT) and NT. The sorghum-wheat/soybean rotation was duplicated so that both sorghum and wheat/soybean phases occurred each year. Treatments were replicated four times.

Conventional tillage operations in sorghum and soybean consisted of disking (100 to 150 mm depth) after harvest, followed by chisel-plowing (200 to 250 mm depth), a second disking (100 to 150 mm depth), forming ridges for planting, and cultivating two or three times during early crop growth. Conventional tillage operations in wheat consisted of disking (100 to 150 mm depth) two to three times following harvest. No soil disturbance occurred under NT, except for planting of all crops and banded fertilizer application in sorghum. Sorghum stalks were shredded following harvest under both tillage regimes.

Nitrogen fertilizer (NH_4NO_3) was banded preplant at 4.5 $g\ N \cdot m^{-2}$ in sorghum, broadcasted during early spring at 3.4 $g\ N \cdot m^{-2}$ in wheat, and not applied to soybean. Sorghum was planted in 1-m-wide rows in mid-March and harvested in early August. Wheat was planted in 0.2-m-wide rows in early November and harvested in late May. Soybean was planted in 1-m-wide rows in early June and harvested in mid October. Plots measured 4 m x 12.2 m. Treatments were arranged as a block design with four replications.

The soil was classified as a Weswood silty clay loam with 35% clay, 52% silt, 13% sand, 9% $CaCO_3$ equivalent, and a pH of 8.2 (1:2, soil:water). Long-term annual temperature is 20°C and rainfall is 978 mm.

2.2 Soil Sampling

Soil samples were collected 57 times during a 2-yr period from July 1991 to June 1993. Sampling was in association with *in situ* determination of soil CO_2 evolution using the static chamber method with alkali absorption and determination of soil temperature, water content, and bulk density (*Franzluebbers* et al., 1995d). Soil cores were collected from 200 to 300 mm to the side of sorghum and soybean rows and from the center between wheat rows during the growing season. During the fallow period, soil cores were collected from near the ridge apex. A soil core (19 mm diam., 200 mm depth) was collected from each of four replications at each sampling date and the four soil cores composited. Extensive temporal soil sampling was considered more suitable to characterize the short-term seasonal variation in soil properties than using limited resources for spatial replication with infrequent temporal sampling.

2.3 Soil Biochemical Properties

Oven-dried soil (60°C, 48 hr) was gently crushed to pass a 5-mm screen. Organic material was not removed, so as to reflect seasonal changes in C input. For determination of SMBC and potential C and N mineralization, three 50-mL beakers with 20, 40, and 40 g of soil were placed in a 1-L glass jar along with a vial containing 10 mL of 0.5 *M* KOH to trap evolved CO_2 and a vial containing 10 mL of water to maintain high humidity. Soil water content was brought to 0.30 $kg \cdot kg^{-1}$ (−0.03 MPa, 0.55 water-filled pore space) with deionized water. Soil was incubated at 25°C for 18 d. CO_2-C was determined by titration with HCl at 3, 7, and 18 d, replacing the alkali trap each time (*Anderson*, 1982). Soil microbial biomass C was determined using chloroform fumigation-incubation (*Jenkinson & Powlson*, 1976) from one of the 40-g subsamples removed at the end of 7 d pre-incubation. The flush of CO_2-C released from the fumigated sample was adjusted with an efficiency factor of 0.41 (*Voroney & Paul*, 1984).

Potential C mineralization was determined as the rate of CO_2-C evolved between 7 and 18 d. We used this time period for estimation of the linear rate of C mineralization based on the observation that 95% of the flush of CO_2-C following rewetting of dried soil was released by 4 to 6 d (*Santruckova* et al., 1993).

Table 1: Yearly mean and seasonal variation in soil physical and biochemical properties to a depth of 200 mm in sorghum-wheat/soybean (S-W/S) and continuous wheat/soybean (W/S) under conventional tillage (CT) and no tillage (NT).

Tabelle 1: Jährlicher Mittelwert und jahreszeitliche Variation von physikalischen und biochemischen Bodeneigenschaften in 0–200 mm Tiefe in einer Sorghum-Weizen/Sojabohne-Fruchtfolge (S-W/S) und einer Weizen/Sojabohne-Fruchtfolge (W/S) mit konventioneller Bodenbearbeitung (CT) und Direktsaat (NT).

	Yearly Mean						Seasonal Variation (%)‡					
	S-W/S			W/S			S-W/S			W/S		
Soil Property†	CT		NT	CT		NT	CT		NT	CT		NT
Soil temperature (°C)	16.9		17.4	17.0		17.5	41		40	42		40
Bulk density ($Mg \cdot m^{-3}$)	1.42	***	1.54	1.46	***	1.52	5	***	2	4		1
Water-filled pore space ($m^3 \cdot m^{-3}$)	0.63	***	0.70	0.59	***	0.70	19	***	14	21		15
CMIN ($g \cdot m^{-2} \cdot d^{-1}$)	2.56	***	3.16	2.89	***	3.78	20	***	12	21	*	8
SMBC ($g \cdot m^{-2}$)	172	***	197	174	***	220	7	**	10	7	*	7
SRAC (mg C $\cdot g^{-1}$ SMBC $\cdot d^{-1}$)	15.0	**	16.2	16.6		17.5	18		9	19		12
NMIN ($g \cdot m^{-2} \cdot d^{-1}$)	0.05	*	0.08	0.06		0.08	89		93	107		76
NMIN ($g \cdot m^{-2} \cdot 18\ d^{-1}$)	4.25	***	6.00	4.99	***	6.69	23	*	23	19		13
Inorganic soil N ($g \cdot m^{-2}$)	4.76		4.62	4.46	***	5.59	19	*	24	20		27

† CMIN = potential carbon mineralization, SMBC = soil microbial biomass carbon, SRAC = specific respiratory activity of soil microbial biomass carbon, and NMIN = net nitrogen mineralization.

‡ Seasonal variation was estimated as the coefficient of variation of yearly means using monthly values.

*, **, and *** indicate significance between tillage regimes within a crop sequence at $P \leq 0.1$, 0.01, and 0.001, respectively.

Specific respiratory activity of SMBC was calculated by dividing the rate of C mineralization from 7 to 18 d by SMBC.

Inorganic N (NH_4-N + NO_3-N + NO_2-N) content of unfumigated soil, which was incubated for 0, 7 (20-g subsample), and 18 d (40-g subsample), was determined after oven-drying (60°C, 24 hr) and passing through a 2-mm screen. A 7-g portion of each sample was shaken with 28 mL of 2 *M* KCl for 30 min, filtered, and the extract analyzed for NH_4-N and (NO_3-N + NO_2-N) using autoanalyzer techniques with a modified indophenol blue method and Cd reduction method, respectively (*Bundy & Meisinger,* 1994). Day 0 of the incubation represented the inorganic soil N content. In preliminary work, NH_4-N concentration was ≈1 mg · kg^{-1} in fresh soil and increased to ≈9 mg · kg^{-1} upon oven-drying. The rate of potential N mineralization was described from the mineralized N between 7 and 18 d, as well as the total N mineralized during 18 d of incubation. The rate of N mineralization from dried and rewetted soil was shown to be linear after an initial flush of N, of which 95% occurred within 2 to 3 d (*Cabrera,* 1993).

2.4 Statistical Analyses

Monthly means were comprised of three sampling dates in January and December, four sampling dates in August and November, five sampling dates in February, May, June, July, and October, and six sampling dates in March, April, and September. Differences in potential C and N mineralization, SMBC, specific respiratory activity of SMBC, and inorganic soil N due to tillage regime and sampling period (*i.e.,* month) within each crop sequence were analyzed with the general linear model procedure of SAS (*SAS Institute Inc.,* 1985) as a randomized block design using sampling date within each month as a blocking criterion. Monthly means of soil properties were separated by LSD at $P \leq 0.1$. Seasonal variation in soil properties was expressed as the coefficient of variation of monthly means.

3 Results and Discussion

3.1 Potential C Mineralization (CMIN)

In sorghum-wheat/soybean and continuous wheat/soybean, CMIN generally increased following crop residue additions, especially under CT (Fig. 1). Seasonal variation in CMIN was greater under CT than under NT (Tab. 1), probably due to greater fluctuations in bulk density and water-filled pore space (*Franzluebbers* et al., 1995d), as well as redistribution of crop residues within the soil profile with tillage operations.

The flush of CO_2-C after rewetting of dried soil exhibited a strong seasonal pattern during the growing season of wheat that was suggestive of rhizodeposition (Fig. 2). Temporal changes in the flush of CO_2-C during the wheat growing season could be attributed to a decline in the availability of previous sorghum or soybean residues during the first 60 d and an increase in wheat roots and decomposition products beginning ≈90 d after planting (*i.e.,* early February). High microbial activity associated with crop residue input and rhizodeposition was associated with a decrease in the amount of N mineralized (Fig. 2), probably due to the low N concentration of residue and rhizodeposition inputs. The flush of CO_2-C after rewetting of a dried soil has been attributed to both biological phenomena and chemical/physical disruption of SOM (*van Gestel* et al., 1991; *Santruckova* et al., 1993; *Sikora* et al., 1994). Seasonal differences in the flush of CO_2-C after rewetting suggest that biological factors played an important role, because its temporal variability was similar to that of root mass development (*Buyanovsky* et al., 1986; *Martens,* 1990).

A larger pool of CMIN in continuous wheat/soybean than in sorghum-wheat/soybean was indicated by the regression parameters describing cumulative C mineralization (Tab. 2). The flush of CMIN following rewetting multiplied by the non-linear mineralization constant ($C_f \cdot k$ from Tab. 2) was 12.4 and 10.9 $g \cdot m^{-2} \cdot d^{-1}$ under CT and 15.8 and 13.4 $g \cdot m^{-2} \cdot d^{-1}$ under NT in continuous wheat/

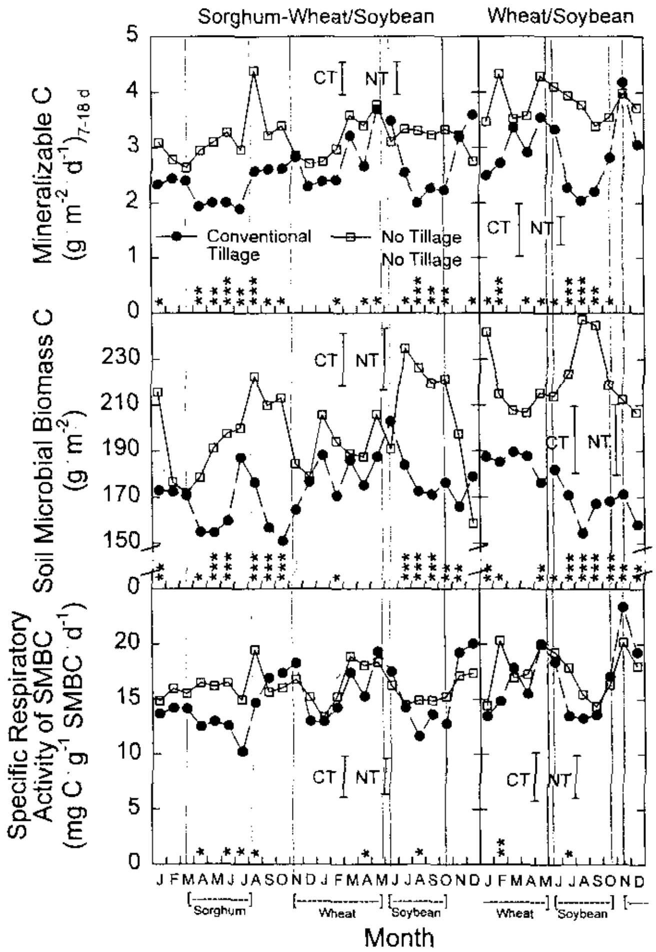

Figure 1: Mean monthly mineralizable C, soil microbial biomass C, and specific respiratory activity of soil microbial biomass C to a depth of 200 mm as affected by crop sequence and tillage. (*, **, and *** indicate significance between tillage regimes at $P \leq 0.1$, $P \leq 0.01$, and $P \leq 0.001$, respectively. Error bar is $LSD_{(P \leq 0.1)}$ for comparison of monthly means within conventional tillage [CT] and no tillage [NT].)

Abbildung 1: Einfluß von Fruchtfolge und Bodenbearbeitungssystem *auf den durchschnittlichen monatlichen mineralisierbaren C, den mikro*bielIen Biomasse-C und die spezifische Atmungsaktivität in 0–200 mm Tiefe. (*, **, und *** geben statistisch signifikante Unterschiede zwischen den Bodenbearbeitungssystemen bei $P \leq 0.1$, $P \leq 0.01$, und $P \leq 0.001$ an. Error bar ist $LSD_{(P \leq 0.1)}$ zum Vergleich von monatlichen Mittelwerten innerhalb konventioneller Bodenbearbeitung [CT] und Direktsaat [NT].)

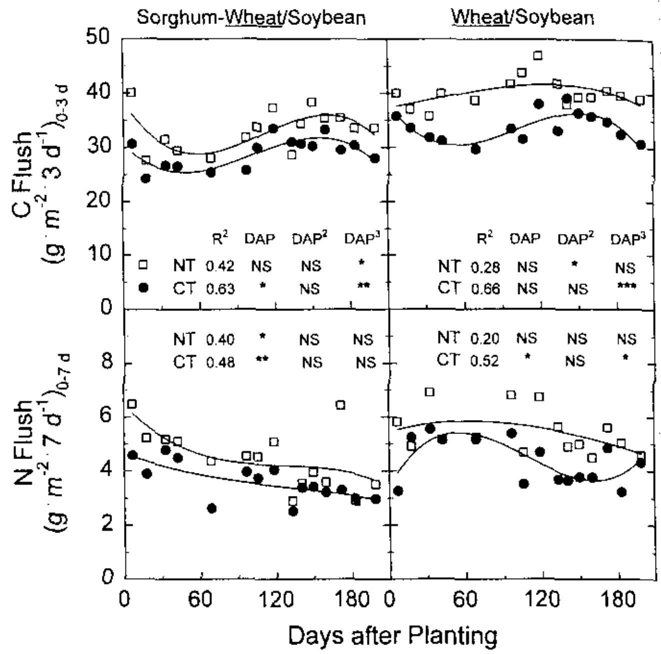

Figure 2: Flush of CO_2-C evolved during the first three days and the flush of inorganic N during the first seven days after rewetting of dried soil to a depth of 200 mm during the growing season of wheat as *affected by crop sequence and tillage. (Each point represents the mean* of two observations. Conventional tillage [CT], no tillage [NT], days after planting [DAP].)

Abbildung 2: Einfluß von Fruchtfolge und Bodenbearbeitungssystem auf die CO_2-Abgabe während der ersten drei Tage und die N-Mineralisierung während der ersten sieben Tage nach Wiederbefeuchtung eines getrockneten Bodens (0–200 mm Tiefe) während der Wachstumspe*riode von Weizen. (Jeder Punkt ist der Mittelwert von zwei Beobach*tungen. Konventionelle Bodenbearbeitung [CT], Direktsaat [NT], Tage nach der Saat [DAP].)

soybean and sorghum-wheat/soybean, respectively. This "instantaneous potential rate of mineralization" has been suggested as an index for assessing the quality of SOM (*Campbell* et al., 1991). The instantaneous C mineralization rate was 9.5, 8.8, and 6.9 $g \cdot m^{-2} \cdot d^{-1}$ under CT and 11.8, 11.4, and 10.8 $g \cdot m^{-2} \cdot d^{-1}$ under NT in monoculture wheat, sorghum, and soybean, respectively in the same soil (*Franzluebbers* et al., 1995c). The instantaneous C mineralization rate was therefore dependent upon cropping intensity, similar to that observed by *Campbell* et al., (1991), in addition to placement of residues with tillage regime. The long-term level of soil organic C in both monoculture (*Franzluebbers* et al., 1995c) and double-cropped systems (*Franzluebbers* et al., 1995d) was related to the instantaneous C mineralization rate ($r=0.85$, $n=10$), suggesting that high residue input was needed to increase the labile and total pools of SOM.

3.2 Soil Microbial Biomass Carbon (SMBC)

In both crop sequences, SMBC exhibited seasonal changes that could be attributed to input of C substrates to the soil via rhizodeposition during the growing season and crop residues following harvest in a manner similar to that observed for CMIN, but with less change in magnitude (Fig. 1). It seems that SMBC responded to C input via crop residue addition to a much greater extent than via rhizodeposition (Fig. 1). Monthly variation in SMBC from continuous wheat under CT in England was 5%, but variation in CMIN was 10% (*Patra* et al., 1990). In several cropping systems under CT in Alberta, seasonal variation in SMBC ranged from 2 to 4% (*McGill* et al., 1986).

Relative differences in SMBC between tillage regimes were less than for CMIN (Tab. 1). Soil under NT for 5 to 13 yr had from 6% less to 49% more SMBC than under CT from several locations in the Midwest, USA (*Doran*, 1987).

Table 2: Non-linear regression equations describing C and N mineralization during 18 d after rewetting of dried soil in sorghum-wheat/soybean (n=24 months) and continuous wheat/soybean (n=12 months) under conventional tillage (CT) and no tillage (NT).

Tabelle 2: Nicht-lineare Regressionsgleichungen zur Beschreibung der durchschnittlichen C- und N-Mineralisierung während 18 Tage nach Wiederbefeuchtung eines trockenen Bodens in einer Sorghum-Weizen/Sojabohne Fruchtfolge (n=24 Monate) und einer Weizen/Sojabohne Fruchtfolge (n=12 Monate) mit konventioneller Bodenbearbeitung (CT) und Direktsat (NT).

	Sorghum-Wheat/Soybean			Wheat/Soybean		
Parameter†	CT		NT	CT		NT
C mineralization: $C_t = C_f \cdot (1 - e^{-k \cdot t}) + BSR \cdot t$						
C_f	33.2	*	36.1	36.9	**	45.1
k	0.328	***	0.371	0.337		0.350
BSR	2.27	***	2.93	2.60	***	3.46
N mineralization: $N_t = N_i + N_0 \cdot (1 - e^{-k \cdot t})$						
N_i	4.61	*	4.47	4.41	***	5.54
N_0	4.58	***	6.37	5.19	***	6.91
k	0.255		0.245	0.255		0.256

† C_t = C mineralization ($g \cdot m^{-2}$) at time t (d), C_f = C mineralization potential of flush following rewetting of dried soil ($g \cdot m^{-2}$), k = non-linear mineralization constant (d^{-1}), BSR = basal soil respiration ($g \cdot m^{-2} \cdot d^{-1}$), N_t = net N mineralization ($g \cdot m^{-2}$) at time t, N_i = initial inorganic N ($g \cdot m^{-2}$), N_0 = N mineralization potential ($g \cdot m^{-2}$).

*, **, and *** between means of each crop sequence indicate significance between tillage regimes at $P \leq 0.1$, 0.01, and 0.001, respectively.

We found 73 to 146% greater SMBC under NT than under CT in the 0 to 50 mm depth, but only 12 to 43% greater SMBC calculated in the 0 to 200 mm depth of this same study (*Franzluebbers* et al., 1994a). Changes in SMBC were less dramatic from planting to flowering to harvest of sorghum and wheat than changes in CMIN (*Franzluebbers* et al., 1994b, 1995b). Less dramatic changes in SMBC would be expected because the flow of mineralizable C through SMB must supply both microbial maintenance and growth (*Martens*, 1990).

3.3 Specific Respiratory Activity of Soil Microbial Biomass Carbon (SRAC)

Small differences in SRAC occurred between tillage regimes (Fig. 1). This similarity in seasonal dynamics between tillage regimes suggests that crop root and residue inputs caused similar microbiological responses, irrespective of the background level of SOM and SMBC induced by long-term tillage. Specific respiratory activity increased with crop residue addition of all crops, but only with root development of wheat. This result may reflect the difference in root density near the soil surface between the shallow, fine roots of wheat and the deeper-penetrating, coarse roots of sorghum and soybean. Response of SRAC to crop residue addition was somewhat more pronounced under CT than under NT, perhaps a result of mixing crop residues throughout the 0 to 200 mm depth. The high level of SRAC at the end of the wheat growing season as a possible result of rhizodeposition tended to blend with the high activity associated with wheat residue addition. Large seasonal changes in SRAC indicate that C inputs via crop residue and rhizodeposition were lost within a few months due to the relatively warm, moist conditions throughout much of the year in southcentral Texas. This rapid turnover rate of available substrates further suggests the need for continual input of organic material in order to increase SOM in the termic temperature regime of the USA.

3.4 Potential N Mineralization (NMIN)

The seasonal pattern of NMIN reflected that of CMIN most times of the year, but was opposite to CMIN at other times (Fig. 3). The pattern of NMIN was opposite to CMIN during the wheat and soybean growing seasons under CT, but increased more than CMIN in the middle of the sorghum growing season and the three months following sorghum under NT in sorghum-wheat/soybean. In continuous wheat/soybean, the pattern of NMIN was opposite to CMIN during the soybean growing season under NT. In a barley (*Hordeum vulgare* L.) cropping system in Sweden, potential mineralizable N was greatest after spring-thaw, lowest during the growing season, and intermediate following crop harvest (*Bonde & Rosswall*, 1987).

Coupling of NMIN with CMIN is common under steady-state conditions or when the available C/N ratio of added substrate is in balance with the background level of SOM (*Jansson & Persson*, 1982). The high level of CMIN and concomitant increase in SMBC led to decreased NMIN at times. For example, in sorghum-wheat/soybean under NT, CMIN and SMBC increased towards the end of the sorghum growing season probably due to rhizodeposition and shortly after harvest due to residue addition, which was associated with a temporary decrease in NMIN (Fig. 1 and 3). As CMIN and SMBC returned to lower levels prior to the wheat growing season, NMIN increased. Another example was the opposite trend of increasing CMIN and decreasing NMIN during the wheat growing season under CT, followed by decreasing CMIN and increasing NMIN early in the soybean growing season. Wheat rhizodeposition products were probably low in N concentration (*Janzen* and *Bruinsma*, 1993), which led

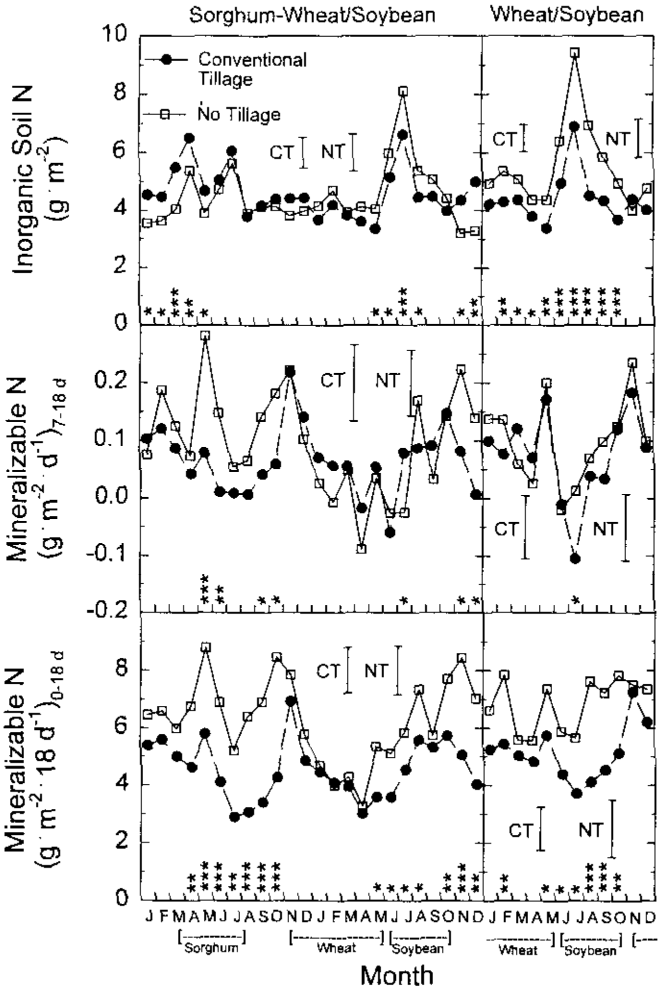

Figure 3: Mean monthly inorganic soil N (NH_4-N + NO_3-N + NO_2-N) content and mineralizable N during 7–18 d and 0–18 d as affected by crop sequence and tillage. (*, **, and *** indicate significance between tillage regimes at $P \leq 0.1$, $P \leq 0.01$, and $P \leq 0.001$, respectively. Error bar is $LSD_{(P \leq 0.1)}$ for comparison of monthly means within conventional tillage [CT] and no tillage [NT].)

Abbildung 3: Einfluß von Fruchtfolge und Bodenbearbeitungssystem auf den durchschnittlichen monatlichen mineralischen N-Gehalt des Bodens (NH_4-N + NO_3-N + NO_2-N) und auf den in 7 bis 18 Tagen und in 0 bis 18 Tagen mineralisierbaren Stickstoff in 0–200 mm Tiefe. (*, ** und *** geben statistisch signifikante Unterschiede zwischen den Bodenbearbeitungssystemen bei $P \leq 0.1$, $P \leq 0.01$, und $P \leq 0.001$ an. Error bar ist $LSD_{(\leq 0.1)}$ zum Vergleich von monatlichen Mittelwerten innerhalb konventioneller Bodenbearbeitung [CT] und Direktsaat [NT].)

to lower NMIN with increasing CMIN (Fig. 2). The low N concentration of wheat (5.0 mg N · g^{-1}) and sorghum (6.5 mg N · g^{-1}) compared to soybean (15.8 mg N · g^{-1}) with high residue input (670 to 840 g · m^{-2} · yr^{-1}) (*Franzluebbers* et al., 1995a), probably contributed to the reduced potential N mineralization, especially after wheat and sorghum residue addition.

3.5 Inorganic Soil N

In sorghum-wheat/soybean, inorganic soil N was high at the beginning of the sorghum growing season due to N fertilization at planting and N accumulation during the 4.5 month fallow after soybean harvest (Fig. 3). A decrease in inorganic soil N occurred in August, indicating immobilization of N as a result of high CMIN and SMBC after sorghum residue addition. Inorganic soil N increased gradually during the fallow period after sorghum under CT, reflecting NMIN coupled with high SRAC during this time. Incorporation of soybean residue, in comparison to surface placement with NT, resulted in higher inorganic soil N during the fallow period between soybean and sorghum, with higher levels maintained early into the sorghum growing season. Over the long-term, reduced *in situ* NMIN of added crop residues with surface placement in NT, in contrast to rapid mineralization of incorporated residues with CT, probably led to higher mean yearly potential NMIN than under CT (Tab. 1).

Mean yearly inorganic soil N in continuous wheat/soybean was greater under NT than under CT, but in sorghum-wheat/soybean was not different between tillage regimes (Tab. 1). Mean annual N uptake by above-ground biomass in continuous wheat/soybean was 16.8 g · m^{-2} in NT and 22.9 g · m^{-2} in CT and in sorghum-wheat/soybean was 13.4 g · m^{-2} in NT and 15.2 g · m^{-2} in CT (*Franzluebbers* et al., 1995a). Higher inorganic soil N and lower N uptake in NT than in CT in continuous wheat/soybean would suggest a sparing effect of crop N demand on inorganic soil N supply. Water-filled pore space was almost always greater under NT (*Franzluebbers* et al., 1995d), discounting the possibility of a confounding effect of water supply on differences in N uptake.

The large seasonal changes in active soil C and N pools indicate that organic inputs from crop roots and residues in addition to temperature and moisture are important considerations in describing the short-term dynamics of inorganic N supply. Characterizing potential soil N availability in diverse crop management systems, therefore, can only be reasonably assessed if samples are collected throughout the year. Results based on single or few sampling events should be interpreted cautiously.

4 Conclusions

These results show that the size and activity of the active soil C and N pools of SOM are seasonally dependent. The extent of seasonal variation in active soil C and N properties was similar between cropping sequences. Seasonal variation in SRAC was similar, but seasonal variation in CMIN and SMBC was different between tillage regimes in both crop sequences. Cultural practices affected these changes in active soil C and N by altering the (i) placement of crop residues with tillage and (ii) quantity, quality, and timing of crop residues with crop species and sequence. More intensive cropping in wheat/soybean than in sorghum-wheat/soybean, as well as either system compared with lower intensity monoculture systems (*Franzluebbers* et al., 1995c), maintained higher levels of active and total

SOM throughout the year, suggesting that increased C input rather than reduced microbial activity led to conservation of SOM in this soil.

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